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The Stellar Populations in the Outer Regions of M33. I. Metallicity Distribution Function[1]

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ABSTRACT

We present deep CCD photometry in the VI passbands using the WIYN 3.5m telescope of a field located approximately 20' southeast of the center of M33; this field includes the region studied by Mould & Kristian in their 1986 paper. The color-magnitude diagram (CMD) extends to I$\sim$25 and shows a prominent red giant branch (RGB), along with significant numbers of asymptotic giant branch and young main sequence stars. The red clump of core helium burning stars is also discernable near the limit of our CMD. The I-band apparent magnitude of the red giant branch tip implies a distance modulus of $(m-M)_I = 24.77 \pm 0.06$, which combined with an adopted reddening of $E(V-I) = 0.06 \pm 0.02$ yields an absolute modulus of $(m-M)_0 = 24.69 \pm 0.07$ (867$\pm$28 kpc) for M33. Over the range of deprojected radii covered by our field ($\sim$8.5 to $\sim$12.5 kpc), we find a significant age gradient with an upper limit of $\sim$1 Gyr ($\sim$0.25 Gyr/kpc). Comparison of the RGB photometry to empirical giant branch sequences for Galactic globulars allows us to use the dereddened color of these stars to construct a metallicity distribution function (MDF). The primary peak in the MDF is at a metallicity of $[Fe/H]\sim$–1.0 with a tail to lower abundances. The peak does show radial variation with a slope of Δ[Fe/H]/ΔR_{deproj} = –0.06 $\pm$ 0.01 dex/kpc. This gradient is consistent with the variation seen in the inner *disk* regions of M33.

[1]Based on observations taken with the WIYN 3.5m telescope. The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories.

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As such, we conclude that the vast majority of stars in this field belong to the disk of M33, not the halo as previously thought.

Subject headings: galaxies: halos, galaxies: individual (M33), Local Group; galaxies:spiral, galaxies: stellar content, galaxies: structure

1. Introduction

In recent years M33 has been the target of many systematic studies. From searches for variable stars to pin down one of the fundamental distance estimates in the Cepheid distance latter (e.g. Macri et al. 2001), to kinematical studies of the stellar populations (e.g. Chandar et al. 2002), to X-ray surveys (e.g. Haberl & Pietsch 2001). However, in spite of M33 being the second closest spiral galaxy after M31, close enough for the brighter members of its stellar population to be resolved, the properties of its field halo stars have received comparatively little attention.

The first attempt to study the field halo stars in M33 using CCDs was that of Mould & Kristian (1986, hereafter MK86). In this classic paper, the authors observed an approximately 5x5 arcmin field (see Fig. 1) with the Palomar 5m telescope along with one of the first generation science-grade CCD detectors, a Texas Instruments 800 x 800 pixel array. Their color-magnitude diagram (CMD), based on aperture photometry of 215 stars transformed onto the Cousins system (Cousins 1976a,b), extends from above the first ascent red giant branch (RGB) tip down to ∼1.5 mags below the tip (I∼22.5). From this diagram, they drew two primary conclusions. First, by comparing the M33 RGB with those of the Galactic globular clusters M92 and 47 Tuc, they found the mean metal abundance of the field stars to be $\langle[M/H]\rangle = -2.2 \pm 0.8$. This result was rather surprising given the much higher metallicity ($\langle[M/H]\rangle > -0.8$) they found for the halo of M31. Second, from the bolometric magnitude of the RGB tip and an adopted reddening of $E(V-I) = 0.06$, they calculated an absolute distance modulus of 24.8 ± 0.2 for M33.

Cuillandre, Lequeux, & Lionard (1999) used the UH8k CCD camera at the prime focus of the CFHT 3.6m to image a 28 x 28 arcmin field in a region of M33 that included the MK86 field. Their $(V, V-I)$ CMD reaches as faint as V ∼ 25.5. Cuillandre et al. (1999) adopt an M33 distance modulus of $(m-M)_0 = 24.82$ and estimate the line-of-sight reddening ($E(V-I) = 0.08$) by averaging values based on the 21-cm line (Hartmann 1994) and from foreground stars (Johnson & Joner 1987). Based on these values, a comparison with the RGB sequences of Da Costa & Armandroff (1990) yields a mean metal abundance of [Fe/H] = –1.0 with a metallicity spread from ∼–1.5 to ∼–0.6 dex for the field halo stars in M33.

This mean abundance is clearly much higher than the value advocated by MK86 and a few tenths of a dex higher than the peak abundance of Milky Way field halo stars (e.g. Norris 1994; Carney et al. 1996;).

Most recently, Davidge (2003) has used the Gemini North 8m telescope equipped with GMOS to image a field located ∼9 kpc in projected distance from M33 (∼15.5 kpc deprojected distance), approximately twice as far out as the MK86 field. The g', r', i', z' CMDs of Davidge (2003) are based on a field of view of only 5x5 arcmin and are not extraordinarily deep, reaching some 2 magnitudes below the tip of the RGB, but they are notable as being the first such M33 data at these extreme galactocentric distances. Davidge's conclusions are twofold. First, based on the color of the upper RGB, Davidge (2003) determines a mean abundance of [Fe/H] $= -1.0 \pm 0.3$ (random) ± 0.3 (systematic) for this region of M33. Second, the presence of a significant number of bright asymptotic giant branch stars suggests that an intermediate-age population exists outside of the 'young star-forming' disk of M33. This latter result is consistent with the work of several investigators (e.g. Sarajedini et al. 1998;2000, Chandar et al. 2002) who have suggested that the halo star clusters in M33 are several Gyr younger than similar clusters in the Milky Way's halo.

Within this context, the present series of papers attempts to shed further light on the field halo stellar population(s) of M33. This first paper presents deep ground-based photometry of the MK86 field along with an analysis designed to probe the metallicity distribution function of this region of M33. We begin with a discussion of the observational material in the next section along with details of the photometric reduction procedure. Section 3 describes our artificial star experiments and how they are used to gauge the photometric completeness and errors. We compare our photometry to that of MK86 in Sec. 4. The analysis portion of the paper begins in Sec. 5 in which we use the luminosity function of the RGB to estimate the distance to M33. In Sec. 6, the radial variations of the stellar populations present in our field are analyzed. Section 7 presents the metallicity distribution function and what it implies for this region of M33. Finally, our results are summarized in Sec. 8.

2. Observations, Image Reduction, and Photometry

We obtained deep V and I images of a field centered about 20′ southeast of the center of M33, or about 10 kpc in deprojected distance. The pointings were centered at $\alpha = 01{:}35{:}15$, $\delta = +30{:}30{:}00$ J2000, chosen to sample the halo field population of M33 and to overlap the photometry obtained by MK86 and so facilitate comparison with their work. Figure 1 shows the position of our field (large square) and the position of the field studied in MK86 (small

square) both relative to the center of M33 (upper right).

Our data were obtained on the WIYN 3.5m telescope at Kitt Peak National Observatory on the night of 1999 March 10 UT as part of the '2-hour queue.' The instrument was the S2KB CCD imager which provided a $0\farcs2$ pixel^{-1} plate scale. The CCD is a 2048×2048 array and provided a $6\farcm8 \times 6\farcm8$ field. The seeing was generally excellent at $\sim 0\farcs7$ allowing us to take full advantage of the fine plate scale. A log of the observations is provided in Table 1. Figure 2 is a reproduction of one of our V-band CCD images.

The night of 1999 March 10 UT was not perfectly photometric, therefore in order to photometrically calibrate the data, we obtained a set of Landolt standards (Landolt 1992) and short exposures of the same M33 fields on 2002 February 11 UT. These calibration data were taken with the WIYN 0.9m telescope on Kitt Peak using the same S2KB CCD imager mounted at the Cassegrain focus. The instrument configuration was identical but on the 0.9m telescope it has a plate scale of $0\farcs6$ pixel^{-1}, and a $20\farcm5 \times 20\farcm5$ field of view. Seeing was $\sim 1\farcs5$ but with the shallower exposures crowding was not a problem. A log of these observations are also provided in Table 1.

We did all preliminary data reduction on both sets of images using the IRAF routines contained in *ccdproc*. The raw CCD frames were processed to fit and remove the overscan level, trim the overscan region, subtract a zero exposure time bias, and finally to flatten the individual pixel responses with appropriate dome flats. The final, flattened images were all flat to $\lesssim 0.2\%$ with the exception of the deep, 3.5 m I-band images which had fringing at the $\sim 0.5\%$ level. Since the peak-to-peak pixel extent of the fringing was much greater than the typical FWHM of point sources in the frame, we made no attempt to correct it.

We measured the aperture photometry of the SA98 standard stars using the IRAF routine *phot*. In each set of exposures of the SA98 field, 35 standards were measured so that the final calibration for the night was determined from 70 measurements. The night was determined to show no evidence of a $(V - I)$ color term, to $\lesssim 0.5\%$, so we simply fit the equations:

$$v = V + v_1 + v_2 \times X_V$$
$$i = I + i_1 + i_2 \times X_I$$

where the capital letters denote standard magnitudes, the lower case letters denote instrumental magnitudes, the X variables are the respective airmasses, and the numbered subscript coefficients are the fit coefficients. The values determined for the calibration coefficients along with their uncertainties are given in Table 2. From these uncertainties and the formal error aperture photometry measurements, the typical zero point uncertainty from these calibration equations is $\sim 1\%$.

After photometrically calibrating the night of 2002 February 11 UT, we calculated a photometric transformation between the shallow M33 exposures taken on that night and the deep M33 exposures taken on the night of 1999 March 10 UT. We measured the instrumental magnitudes for the deep exposures using the ALLSTAR routine from DAOPHOT II (Stetson 1987). A transformation for each deep exposure was calculated independently due to changing airmass, seeing, and possible transparency changes. There were typically ~ 25 stars in each transformation. The coefficients of these transformations are given in Table 3. Note that we found no color term in the I-band transformations so they are simple zeropoint offsets. The V-band did have a $(V-I)$ color term of $\sim 3.5\%$. The V-band transformations were calculated by solving a least squares fit to the equation:

$$(V_{stand} - v_{inst}) = c_1 + c_2 \times (V - I)_{stand}$$

and the I-band transformations were calculate by finding the mean difference $\langle(I_{stand} - i_{inst})\rangle$. To exclude saturated stars in the deep 3.5m data, blends in either data set, mismatches between the sets, and any stars contaminated by cosmic rays, the least squares fits for the V-band data were 2σ clipped and iterated until no additional stars were eliminated and the I-band mean differences were 2.5σ clipped. The number of stars listed in the last column of Table 3 are the number surviving the clipping and used to calculated the calibration. The typical zero-point uncertainty in the calibration of the frames is ~ 0.03 mag.

After culling the data to remove spurious detections, extragalactic sources, and unreliable detections, (see discussion below) the final calibrated data set contains 19,350 stars, measured in both V and I. Table 4 presents all of these data and Fig. 3 presents an I versus $(V-I)$ color magnitude diagram. The CMD shows a well defined upper giant branch with a first ascent giant branch tip around $I \sim 21$, and a population of asymptotic giant branch (AGB) stars above the tip. The upper giant branch shows inherent scatter larger than that expected from just photometric error, and so there is likely to be an intrinsic dispersion in the age and/or metallicity of the sample. This is also apparent in the significant number of blue main sequence stars (i.e. I = 23-24 and $(V-I) \sim 0$), the presence of stars brighter than the RGB tip, and the appearance of a red clump dominated by core-helium burning stars at I$\sim$24.3. In the sections below we examine these features in detail.

Although we do not possess a CMD of a field away from M33, we can simulate the appearance of such a diagram using the Galaxy model of Robin et al. (1996, and references therein). Using the latest version of their model available from their web page,[1] we have generated colors and magnitudes for stars in the line of sight to our M33 field. These are

[1] $http://www.obs-besancon.fr/www/modele/modele\_ang.html$

shown as the gray points in Fig. 4 overplotted on our M33 CMD from Fig. 3. Note that the simulated CMD includes the effects of photometric error (Fig. 7) but not incompleteness (Fig. 6). Figure 4 shows that some of the scatter seen redward of V–I $\sim$ 2 in the range 22$\lesssim$I$\lesssim$24 is due to field star contamination. In addition, although some stars above the first ascent RGB tip likely do not belong to M33, the majority of the AGB population with V–I$\gtrsim$2.2 probably does. Lastly, we note that essentially all of the blue stars (V–I$\lesssim$0.4) are likely to belong to M33.

3. Completeness and Photometric Error Analysis

In order to understand details about the CMD for a field with such a complex mixture of stellar populations, we need to quantitatively determine the photometric accuracy and star detection efficiency of our photometric measurements. To do this we created a set of artificial stars of known magnitude and placed them on each data frame and then measured their photometry using a procedure identical to the procedure used with the real stars. Since image crowding may be a limiting factor, we placed the artificial stars on the images in a regular grid pattern, so that no where on the frames do they significantly increase the image crowding.

3.1. Generation of Artificial Stars

We generated the artificial stars to be introduced into the data frames via the following procedure. First we fit analytic functions to three different regions of the observational CMD as displayed in the left panel of Fig. 5. Region one (R1) is the lower asymptotic giant branch which we fit with a second order polynomial in I. Region two is the upper giant branch, which we fit with a line in I. Region three is dominated by young main sequence stars. The scatter proved too large for any kind of formal fit; as a result, we represented it using a line from $23 \leq I \leq 24.5$. In both R1 and R2 the fits were least squares fits that were 2σ clipped with no iterations.

We then used these analytic expressions to populate each section of the CMD. We extrapolated the R1 fit up to $I = 20$ and distributed 540 stars randomly along the fit between $20 \leq I \leq 22$. We only used this relatively small number of stars because completeness is not at question in this magnitude range. We only needed to test the photometric accuracy. We extrapolated the R2 fit down to $I = 26$ to be sure to populate the artificial stars to magnitudes well below our detection limit. Since this set is to be used for the determination

of completeness as well as photometric accuracy, we randomly distributed 9135 stars along the extrapolated fit throughout this entire range. The line segment representing the stars in R3 was randomly populated with 325 stars. In total, we generated 10,000 artificial stars.

The 10,000 artificial stars were distributed across each frame in a 100×100 grid. The origin of this grid was pixel $(50, 50)$ in the first V frame with stars distributed every 19.5 pixels along each axis. The exact positions of the stars were their respective grid center ± 0.5 pixels randomly determined for each star so that the positioning of each star relative to the pixel grid would not be regular. Magnitude offsets between each frame were determined and the coordinate transformation of each subsequent frame onto the system of the first V frame (v1) was calculated; the input coordinates and magnitudes of the artificial stars were then appropriately offset. We used the DAOPHOT II routine ADDSTAR to calculate the flux and place each artificial star in each of the 7 data frames.

We measured the photometry and processed the photometry lists from the 7 frames containing the artificial stars in a manner identical to the original data frames. The resulting photometry of the artificial stars is shown by the black points in the right panel of Fig. 5. The solid grey lines in the right panel indicated the input colors and magnitudes, so the scatter in the plot gives a sense of the ultimate photometric accuracy, with the caveat that the vast majority of the points are essentially coincident with the grey lines.

3.2. Completeness

To get a complete understanding of our measured photometry, we need to understand our detection efficiency as a function of magnitude (i.e., the completeness). The I magnitudes of the artificial data were generated randomly with emphasis on the dimmer part of the magnitude range, and then corresponding V magnitudes were calculated to place each star along one of the sequences described above. As a result the input I magnitudes span $20 \leq I \leq 26$ whereas the V magnitudes do not go as bright and only span $22.3 \lesssim V \lesssim 26.4$.

Figure 6 is a plot of the completeness as both a function of V and I in 0.25 mag bins. The V detections are 100% complete down to the 22.75–23 mag bin and the I detections are 100% complete down to the 21.75–22 mag bin. Both bands then have a number of magnitude bins where the completeness is very nearly 100%, and then fall off quickly in the usual fashion.

All detections in each frame, real and artificial stars, were filtered through a set of statistical parameters to prevent non-stellar detections from appearing in our dataset. In addition to reporting an instrumental magnitude and error for each measurement, ALLSTAR

also calculates a goodness of fit to the empirical PSF of the detection (χ) and a measure of the similarity of the detection to a point source (*sharp*). To avoid keeping measurements of bad pixels, cosmic ray hits, error peaks in the halos of saturated stars, and extended objects like background galaxies, we filtered the ALLSTAR output lists to remove all objects with err > 0.6 mag or err $> 2\sigma \times \langle \mathrm{err} \rangle$ at a given magnitude, $\chi > 3$, and $|\mathrm{sharpness}| > 0.5$. Finally, both real and artificial stars are kept in the dataset only if they appear on at least 2 of the 3 V images and 3 of the 4 I images. (In the case of the artificial stars, they were also considered found if they fell off the edge of a given frame but were found in all of the frames they did fall upon.) As a result, the detection probability falls significantly below 100% near $V \sim 25$ and $I \sim 24$.

3.3. Photometric Error

A comparison of the absolute value of the difference between the input magnitudes and the measured magnitudes and the error estimates reported by ALLSTAR shows that the two are in good agreement. Figure 7 illustrates the comparison between the reported errors (lower panels), and the mean of the absolute value of the difference between the input magnitudes and the measured value averaged in bins 0.25 mag in width. The error bars in the top panels are the scatter in each bin. The curves are natural logarithm least-squares fits to the reported errors in the lower panels, which are plotted over the binned measured errors in the top panels. Note that these curves are in good agreement with the measured errors. The only significant deviation is at magnitudes dimmer than $I = 25$ and $V = 26$ both of which are beyond the point where our completeness of detection begins to fall off rapidly.

4. Comparison with the Photometry from Mould and Kristian

To make a direct comparison of our photometric measurements to those of MK86, we used their finder chart and data tables to find the coordinate transformation between the two data sets. We then calculated the difference between our measured V and I photometry and theirs. Excluding differences > 1.0 mag which are likely mismatches or extreme variable stars, the I band comparison had 197 stars and the V band 188. We fit equations of the form:

$$(m_{\mathrm{TSB}} - m_{\mathrm{MK}}) = c_1 + c_2 \times (V - I)_{\mathrm{TSB}}$$

where TSB denotes values from our photometry and MK denotes values from Mould and Kristian. The resulting fit coefficients are tabulated in Table 5. The I band transformation

has a small but definite color term, but the V band transformation has a much less significant color term. As an alternative, we also calculated a simple zeropoint offset between the two data sets. These values are also presented in Table 5. The I band offset is essentially zero, but the scatter in the residuals is larger than the scatter around the fit which includes the color term. The V band has a 0.121 magnitude zero point offset, but in spite of its color term being small in the linear fit, the scatter in the residuals of the simple zeropoint offset are also larger than about the linear fit.

Whichever transformation is used, the scatter in the residuals is always $\gtrsim 0.2$ mag for both bands. This suggests that the uncertainty in Mould and Kristian's photometric measurements was a little larger than they estimated, and likely a result of unresolved star light contaminating their aperture photometry. Additionally, the color term in the I band transformation means that there is an offset between our (V–I) colors and those of MK86. Some of the conclusions we draw from our data are different than those of MK86 primarily because of these disagreements in the photometry.

5. Luminosity Function and the Tip of the Giant Branch

We constructed the I-band luminosity function of our field by selecting stars from the I versus $(V-I)$ CMD (Fig. 3). We selected all stars brighter than $I = 24$ that fell within a band 0.75 mags in width centered on the first ascent giant branch locus. We also included any stars brighter than $I = 21$ which fell redward of the blue edge of this band extrapolated up to $I = 18$. The resulting luminosity function is displayed in Fig. 8. Based on the simulated field CMD shown in Fig. 4, we estimate that the number of contaminating field stars in this LF is small compared to the number of M33 stars. This is supported by the findings of MK86, who reached the same conclusion.

A number of features are apparent from this luminosity function. The first ascent giant branch is approximated well by a power law. A power law fit to the bins in the range $20.75 \leq I \leq 24$ results in a line with slope, $\alpha = 0.431 \pm 0.008$, as indicated by the heavy solid line in the figure. We restricted the luminosity function to magnitudes brigher than $I = 24$ because this is our >95% completeness limit (see Fig. 6). Inspecting the bins at brighter magnitudes, the first bin to significantly depart from the power law is the bin centered at 20.625. This suggests that the tip of the first ascent giant branch (TRGB) must fall somewhere between this bin and the 20.875 mag bin so that $I \sim 20.75$. Stars brighter than this tip are mostly AGB stars in M33 up until $I \sim 19.75$ at which point the level reaches that expected for forground contamination.

The tip of the red giant branch is the last stage of a star's life before it begins He burning on the zero-age horizontal branch. Many studies have shown that $M_I^{\rm TRGB}$, the I-band absolute magnitude of the TRGB, is remarkably constant over a wide range of metallicities and ages (Da Costa & Armandroff 1990; Lee et al. 1993; Bellazzini et al. 2001). Hence, one can estimate $I_{\rm TRGB}$, the I-band apparent magnitude of the TRGB, to obtain a direct measurement of the apparent distance modulus for a stellar population.

To locate $I_{\rm TRGB}$ in a systematic and reproducable way, we convolved the LF of stars in the color range $1.2 < ({\rm V}-{\rm I}) < 3.0$ with a Gaussian-smoothed Sobel filter weighted by the Poisson noise at each magnitude (Sakai, Madore, & Freedman 1996; Sakai et al. 1997). The edge detector is very sensitive to noise in the LF so one must restrict attention to a small range of magnitudes which are likely to include the TRGB. We chose to examine the range 20.75 ± 0.4 mag because it encompasses previous estimates (Mould & Kristian 1986; Lee et al. 1993; Kim et al. 2002) and based on our examination of the LF above. Figure 9 shows the logarithmic LF and edge detector response in this magnitude range. The highest peak in the filter response occurs at ${\rm I_{TRGB}} = 20.75 \pm 0.02$.

To estimate this random error we ran a series of bootstrap simulations in a manner similar to that of Méndez et al. (2002). The LF was randomly resampled with replacement and each star was perturbed by randomly drawing from a Gaussian distribution with standard deviation equal to the star's error. The edge detector was then applied to the resulting new LF. We repeated this process 50 times resulting in 50 estimates of the TRGB. We found that these estimates were well fit by a Gaussian with a standard deviation of 0.02 mag which we adopt as the random error in our estimate of $I_{\rm TRGB}$.

Given this value of $I_{\rm TRGB}$, we now proceed to determine $M_I^{\rm TRGB}$ as follows. We use Eq. 4 of Bellazzini et al. (2001),

$$M_I^{TRGB} = 0.14[{\rm Fe/H}]^2 + 0.48[{\rm Fe/H}] + 3.66,$$

to calculate $M_I^{\rm TRGB}$ using an initial guess for the peak metallicity of the population. We then use the resultant distance to construct a metallicity distribution function as described in Sec. 7. The peak metal abundance of this distribution is input into the above equation as the next guess for the peak [Fe/H]. This iterative procedure converges quickly to a solution yielding $M_I^{\rm TRGB} = -4.02 \pm 0.05$. Combined with our value for $I_{\rm TRGB}$, we find $(m-M)_I = 24.77 \pm 0.06$, where the quoted uncertainty includes errors in the measurement of $I_{\rm TRGB}$ along with random (0.02 mag) and systematic (0.03 mag) errors in the photometry. With our adopted reddening of $E(V-I) = 0.06 \pm 0.02$ and $A_I = 1.31E(V-I)$ (von Hippel & Sarajedini 1998), we obtain an intrinsic distance modulus of $(m-M)_0 = 24.69 \pm 0.07$ for M33. This value is within the range of distances tabulated by Kim et al. (2002). However, it is significantly greater than

the result of McConnachie et al. (2004), who find $(m-M)_0 = 24.50 \pm 0.06$ also based on the TRGB. The reasons for this difference are unclear at the moment.

6. Radial Population Variations

Adopting the position angle (23^o) and inclination (56^o) of M33 derived by Regan & Vogel (1994) and the distance modulus based on the TRGB, we have computed deprojected radial positions relative to the center of M33 for each star in our sample. Using these, Fig. 10 shows CMDs for our M33 data divided into four radial bins. The dashed boxes represent the main sequence (MS) region (19.0≤I≤23.5, –0.5≤(V–I)≤0.5), the asymptotic giant branch (AGB) region (19.7≤I≤20.7, 1.4≤(V–I)≤3.5), and the red giant branch (RGB) region (20.85≤I≤22.85, 1.0≤(V–I)≤2.15). The MS is representative of stars with ages younger than ∼0.5 Gyr, the AGB is mainly stars between ∼2 Gyr and ∼8 Gyr, and the RGB is dominated by stars older than ∼8 Gyr (see Fig. 12). Inspection of Fig. 10 suggests that the mean age of the M33 stellar population is increasing as we proceed to larger galactocentric distances in our observed M33 field.

In order to quantify this impression, Fig. 11 shows the radial behavior of the various 'age tracer' populations we have identified above. The filled squares in Fig. 11 show the variation in the stellar density of all stars that are above our 95% completeness limit (V$\lesssim$25, I$\lesssim$24). The open circles, open squares, and filled circles represent the RGB, AGB, and MS regions, respectively. For each region, we have subtracted off the foreground field-star contamination determined from Fig. 4 and then divided by the total stellar density at each radius to account for the overall decrease in the density as R increases. The lines are the weighted least squares fits to each set of points. We see that the inner regions of our M33 field are, in the mean, younger than the outer regions; this is most dramatically illustrated by examining the MS region.

To estimate the age gradient in our field, we proceed as follows. First, we note that the age gradients implied by the three CMD regions (MS, AGB, RGB) must be consistent with each other. As such, we concentrate on the MS region because the gradient is most conspicuous there. Based on the locations of the isochrones in the MS region of the CMD in Fig. 12, we estimate an upper limit of 1 Gyr for the total age gradient in our M33 field. We will investigate this question further in Paper II where we present a synthetic CMD analysis we have performed using the starFISH code of Harris & Zaritsky (2001).

7. Metallicity Distribution Function

It is instructive to examine the distribution of RGB stars as compared with empirical RGB sequences for a set of standard Galactic globular clusters (GC). This approach has historically been used to derive a metallicity distribution function (MDF) for stellar populations (e.g. Durrell, Harris, & Pritchet 2001; Sarajedini & Van Duyne 2001; Harris & Harris 2002). It involves using the dereddened color of RGB stars as a surrogate for metal abundance under the assumption that all stars on the dominant RGB sequence are old (i.e. $\gtrsim$10 Gyr). In this section, we apply this technique to our CMD and investigate the properties of the resultant MDF.

7.1. Construction and Global Properties

The upper panel of Fig. 12 shows our M33 CMD along with Z=0.004 ([Fe/H]$\sim$–0.7) theoretical isochrones (Girardi et al. 2002) for ages of 10^7, 10^8, $10^{8.5}$, 10^9, and 10^{10} years. A distance modulus of $(m-M)_I = 24.77$ and a reddening of $E(V-I) = 0.06$ have been applied to the photometry. We see that stars with a range of ages are present in our field. However, the RGB stars appear to be dominated by a population that is of order 10^{10} years old, which means that the majority of the resultant stellar metallicities will not be significantly affected by age. This assertion is supported by preliminary StarFISH synthetic CMD work we have performed. The full starFISH analysis and a complete discussion of the results will be presented in Paper II of this series.

The lower panel of Fig. 12 illustrates our technique for constructing the MDF by showing empirical GC RGBs formulated by Saviane et al. (2000) for $[Fe/H]$ values of –2.0, –1.5, –1.0, and –0.7 dex. For each star with $-3.9 \geq M_I \geq -2.4$ and $1.0 \leq (V-I)_0 \leq 2.2$, we can convert dereddened color to metal abundance using this grid of RGBs. We have chosen this range of color and magnitude to minimize the influence of old AGB stars that are bluer than the first ascent RGB. The result of this exercise is shown in Fig. 13. The filled circles in the upper panel represent the binned histogram of metallicities for the 1123 RGB stars that meet our selection criteria. The solid line is the generalized histogram of these values constructed by adding up unit Gaussians with widths given by the error in each metalliciity. The generalized MDF has at least two advantages over the binned one. First, it is not subject to the vagaries associated with binning - the choice of endpoints and the bin sizes. Second, genuine (and artifactual) features of the distribution are revealed when the errors are taken into account in its construction. We see that the MDF exhibits a prominent peak at [Fe/H]~ -1.1, a possible secondary peak at [Fe/H]~ -1.4, and a gradual tail to lower metallicities.

To demonstrate the effects of reddening uncertainties on the construction of the MDF, the lower panel of Fig. 13 shows the generalized MDF from the upper panel (solid line) along with two additional distributions - one constructed using a reddening that is 0.02 mag smaller than our adopted value of $E(V - I) = 0.06 \pm 0.02$ (dashed) and the other using a value that is 0.02 mag larger (dotted). We note that the essential features of the distribution discussed above are unchanged.

As noted above, our preliminary StarFISH results suggest that the ages of the RGB stars are not likely to significantly affect the derived MDF. We estimate that the metallicity of the peak *could* be biased downward by 0.1 to 0.2 dex due to the presence of stars younger than ∼8 Gyr in the RGB sample that produced the MDF. Thus, the true peak of the MDF could be as high as [Fe/H]~ -0.9. This number is somewhat uncertain, but it does represent a likely upper limit on the effect of age on the MDF peak.

7.2. Radial Abundance Variation

Figure 14a plots the metal abundance of each RGB star as a function of its deprojected radial location in kiloparsecs. A robust iterative 2-σ-rejection least-squares fit (Sarajedini & Norris 1994) to these data reveals a modest, yet statistically significant, gradient yielding

$$[Fe/H] = -0.06(\pm 0.01) R_{deproj} - 0.45(\pm 0.08),$$

as shown by the solid line in Fig. 14a.

Figure 14b illustrates radial abundance gradients derived from other M33 populations compared with our data. First, we divided our data from Fig. 14a into two bins at R=10.5 kpc. We then fit the dominant peak of the MDF in each bin with a Gaussian function. The resultant peak metallicities are plotted as open circles in Fig. 14b. The filled circles in Fig. 14b are the M33 disk regions studied by Kim et al. (2002, hereafter KKLSG). They constructed CMDs based on Hubble Space Telescope Wide Field Planetary Camera 2 observations of 10 M33 disk regions. Their CMDs extend to I∼27 and sample the disk stars in M33. KKLSG followed a procedure similar to our's (thus allowing an intercomparison of the results) and used the dereddened color of the RGB to estimate the mean metal abundance in each of their fields. A least-squares fit to all of the filled circles yields

$$[Fe/H] = -0.05(\pm 0.01) R_{deproj} - 0.55(\pm 0.02)$$

shown by the solid line. If we exclude the two innermost points, where the image crowding may have been problematic, we find

$$[Fe/H] = -0.07(\pm 0.01) R_{deproj} - 0.48(\pm 0.04),$$

which is illustrated by the long dashed line. In order to reliably compare these abundance gradient relations with our result, we need to adjust our data for the difference in distance modulus between the present work [$(m-M)_I = 24.77$] and that of KKLSG [$(m-M)_I = 24.89$]. Having done this, we find that

$$[Fe/H] = -0.07(\pm 0.01)R_{deproj} - 0.49(\pm 0.09),$$

which is statistically identical to both of the lines derived by KKLSG. This suggests that the vast majority of stars in our M33 field belong to the disk population of that galaxy, *not* the halo as previously thought (e.g. MK86). If this assertion is borne out, then the M33 stellar disk would extend out to ∼12 kpc.

At this point, it is important to note that the slight radial age variation determined in Sec. 6 would have a negligible effect on our metallicity gradient (Fig. 14a). The Girardi et al. (2002) isochrones predict a change in the implied metallicity of ∼0.05 dex/Gyr due to the effect of age on the colors of RGB stars at M_I=–3.5. Given our upper limit of 1 Gyr for the total age gradient in our field, this implies a differential correction of ±0.025 dex from the inner regions to the outer regions. The resultant "corrected" slope would be Δ[Fe/H]/ΔR_{deproj} = –0.07, which is still consistent with the equations given above.

For reference, the dotted line in Fig. 14b shows the radial abundance variation of the HII regions as derived by Kim et al. (2002, see their Fig. 5). Lastly, the open squares in Fig. 14b are the nine M33 halo globular clusters from Sarajedini et al. (2000). They exhibit no radial abundance gradient. This is one signature of a chaotic fragmentation type formation scenario similar to Galactic globular clusters outside 8 kpc from the Galactic center, which also show no radial abundance gradient (Searle & Zinn 1978). As pointed out by Sarajedini et al. (1998,2000), the M33 halo clusters suffer from the second parameter effect again analogous to the outer Galactic halo globulars. If our M33 field was dominated by halo stars, then there would be no significant radial abundance gradient among the stars just like the halo clusters.

8. Summary and Conclusions

In this work, we present deep VI photometry of a field in M33, that includes the region studied by Mould & Kristian(1986), observed with the WIYN 3.5m telescope. Based on the CMD, which reaches past the helium burning red clump, we draw the following conclusions.

1) The I-band apparent magnitude of the TRGB is measured to be $I_{TRGB} = 20.75 \pm 0.04$, where the error includes the measurement error (0.02 mag) along with random (0.02 mag) and systematic (0.03 mag) errors in the photometry.

2) The I-band apparent magnitude of the TRGB implies a distance modulus of $(m-M)_I = 24.77 \pm 0.06$, which combined with an adopted reddening of $E(V-I) = 0.06 \pm 0.02$ yields an absolute modulus of $(m-M)_0 = 24.69 \pm 0.07$ (867±28 kpc) for M33.

3) By examining the spatial properties of stars in various parts of the CMD, we find that, over the range of deprojected radii covered by our field (∼8.5 to ∼12.5 kpc), there is a significant age gradient with an upper limit of ∼1 Gyr (i.e., ∼0.25 Gyr/kpc).

4) Using the empirical RGB grid constructed by Saviane et al. (2000), we have converted the dereddened color of each RGB star to a metallicity. The resultant metallicity distribution function (MDF) displays a primary peak at a metallicity of $[Fe/H]$∼–1.0 with a tail to lower abundances. The peak shows a radial variation with a slope of Δ[Fe/H]/ΔR_{deproj} = –0.06 ± 0.01 dex/kpc. This gradient is consistent with the variation seen in the inner *disk* regions of M33. Therefore, we conclude that the vast majority of stars in this field belong to the disk of M33, not the halo as previously thought.

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Fig. 1.— A finder chart for our field (large box) and the relative positions of the Mould & Kristian (1986) field (small box) and the center of M33. North is up and East is to the left. The image is approximately 30′ wide.

Fig. 2.— A V-band CCD image of our M33 field. The field is 6.8 x 6.8 arcmin. North is up and east to the left.

Fig. 3.— I versus $(V - I)$ color magnitude diagram of the entire sample.

Fig. 4.— Same as Fig. 3 except that the simulated distribution of non-M33 stars is overplotted as the filled circles.

Fig. 5.— Generation of artificial stars. The left panel shows the three regions in which analytic functions were fit to the observed distribution of stars. Region 1 (R1) contains the AGB. We fit a second order polynomial using 2σ clipped least squares and then extrapolated the polynomial to $I = 20$. Region 2 (R2) contains the upper giant branch. We fit a line using 2σ clipped least squares. The line was then extrapolated down to $I = 26$. Region 3 (R3) contains the young main sequence. The scatter precluded fitting any analytic function so a line bisecting the region was chosen. The input data generated from the analytic functions are shown in the right panel by the grey solid lines. The black points indicate the measured artificial data. See text for details.

Fig. 6.— Completeness as a function of magnitude. The open circles show the completeness of the V band data and the filled circles the I band data, both in bins of 0.25 mag. The V detections are 100% complete down to the 22.75–23 mag bin and the I detections are 100% complete down to the 21.75–22 mag bin. Both bands then have a number of magnitude bins where the completeness is very nearly 100%, and then fall off quickly in the usual fashion. This protracted fall off is caused by the filtering process we preformed on all of the data to excluded erroneous detections. See the text for details.

Fig. 7.— Measured error and estimated error. The bottom panels show the photometric measurement errors reported by ALLSTAR for the artificial data. The curve in each plot is the least squares fit to the equation $\ln(\mathrm{error}) = a + b \times \mathrm{mag}$. These curves are plotted in the respective upper panels which also show the mean difference between the input magnitudes and the measured magnitudes binned in 0.25 mag bins. The error bars are the scatter in each bin. Note that the estimated errors are a very good estimated of the actual errors in measurment down to $I = 25$ and $V = 26$ at which point the measured magnitudes are systematically brighter than the error estimates suggest. These magnitudes are much fainter than the level where the data are 100% complete and so well below the magnitude range we use in our analysis.

Fig. 8.— The I-band luminosity function for giant stars in M33. The histogram is the I-band luminosity function for selected stars from our I versus $(V - I)$ CMD (see text for selection details). The heavy solid line is a power law fit in the range $20.75 \leq I \leq 24$, and has a slope, $\alpha = 0.431 \pm 0.008$. The first significant departure from this power law toward brighter magnitudes occurs between the bins centered at 20.625 and 20.875 suggesting that the tip of the first ascent giant branch is around $I = 20.75$.

Fig. 9.— A plot of the results from the edge detection algorithm. In the top panel is the logarithm of the Gaussian-smoothed luminosity function for color-cut stars in the neighborhood of the TRGB. The bottom panel shows the edge detector response. The vertical line marks the position of the TRGB at $I = 20.75$ (see text for details).

Fig. 10.— The radial variation of the M33 CMD in our field. The data are arbitrarily divided into four radial bins based on deprojected radial distances in kiloparsecs. The dashed boxes represent the main sequence (MS) region ($19.0 \leq I \leq 23.5$, $-0.5 \leq (V-I) \leq 0.5$), the asymptotic giant branch (AGB) region ($19.7 \leq I \leq 20.7$, $1.4 \leq (V-I) \leq 3.5$), and the red giant branch (RGB) region ($20.85 \leq I \leq 22.85$, $1.0 \leq (V-I) \leq 2.15$). The MS is representative of stars with ages younger than $\sim$0.5 Gyr, the AGB is mainly stars between $\sim$2 Gyr and $\sim$8 Gyr, and the RGB is dominated by stars older than $\sim$8 Gyr (see Fig. 12).

Fig. 11.— The radial variation of star counts in our M33 field. The filled squares in the upper portion of the diagram show the behavior of all stars above our 95% completeness limit (V$\leq$25, I$\leq$24). The stellar densities in the MS (filled circles), AGB (open squares), and RGB (open circles) regions are scaled by the total number at each radius and plotted in the lower part of the figure. The contribution from stars in the line of sight has been subtracted off at each radius. The lines represent weighted least squares fits to each set of points.

Fig. 12.— The upper panel shows our M33 CMD along with the Girardi et al. (2002) isochrones for Z=0.004 and ages of 10^7, 10^8, $10^{8.5}$, 10^9, and 10^{10} years. The lower panel illustrates our M33 CMD along with the Saviane et al. (2000) empirical RGB grid for $[Fe/H]$ values of –2.0, –1.5, –1.0, and –0.7 dex.

Fig. 13.— The upper panel shows the metallicity distribution function (MDF) for our M33 field. The filled circles represent the binned histogram while the solid line is the generalized histogram. The MDF has been constructed by comparing RGB stars in the range $-3.9 \geq M_I \geq -2.4$ and $1.0 \leq (V-I)_0 \leq 2.2$ with the Saviane et al. (2000) empirical RGB grid. The lower panel illustrates the effects of changing the adopted reddening by ± 0.02 mag in E(V–I).

Fig. 14.— Plots of metal abundance as a function of deprojected radial position in kiloparsecs for various populations in M33. The open circles in the upper panel represent individual RGB stars in our M33 field. The solid line is an iterative 2-σ rejection least-squares fit to these data showing a significant abundance gradient in this range of galactocentric distances. The filled circles in the lower panel are the M33 disk regions studied by Kim et al. (2002). The solid line is the fit to all of the filled circles while the dashed line is the fit excluding the inner two points. The dotted line is the radial abundance variation of the HII regions as derived by Kim et al. (2002). The open squares are the nine M33 halo globular clusters from Sarajedini et al. (2000). Lastly, the open circles in the lower panel are mean metallicities and radial positions of the M33 stars shown in the upper panel.

Table 1. Log of Observations

Field	Date (UT)	Band	Exposure Times (s)	Field Center (J2000) RA	DEC
M33	1999-03-10	V	800	01:35:15	30:30:00
M33		V	800	01:35:15	30:30:12
M33		V	800	01:35:14	30:30:23
M33		I	1100	01:35:14	30:30:23
M33		I	1100	01:35:15	30:30:12
M33		I	1100	01:35:15	30:30:00
M33		I	1100	01:35:14	30:30:12
SA98	2002-02-11	V	60	06:52:13	-00:19:02
SA98		V	60	06:52:12	-00:19:16
SA98		I	50	06:52:13	-00:19:02
SA98		I	50	06:52:12	-00:19:16
M33	2002-02-11	V	600	01:36:00	30:27:51
M33		V	600	01:35:57	30:26:20
M33		V	600	01:36:07	30:28:20
M33		I	300	01:35:58	30:26:20
M33		I	300	01:36:02	30:27:20
M33		I	300	01:36:06	30:28:20

Table 2. Photometric Coefficients for 2002 February 11

Coefficient	Value	Uncertainty
v1	3.2913	0.0072
v2	0.1337	0.0054
i1	4.0270	0.0098
i2	0.0826	0.0075

Table 3. Photometric Transformation Coefficients

Frame	Zero Point	Color Term	Number
V1	7.036 ± 0.010	0.040 ± 0.007	26
V2	7.040 ± 0.012	0.033 ± 0.008	22
V3	6.998 ± 0.012	0.039 ± 0.008	27
I1	6.965 ± 0.032	$\cdots$	24
I2	6.980 ± 0.032	$\cdots$	26
I3	6.959 ± 0.030	$\cdots$	29
I4	7.033 ± 0.028	$\cdots$	24

Table 4. Calibrated Stellar Photometry and Positions

ID	RA	DEC	I	err	V-I	err
	(J2000.0)		(mag)	(mag)	(mag)	(mag)
1	01:35:02.47	30:31:14.8	16.587	0.005	0.594	0.006
2	01:35:15.53	30:29:39.2	16.739	0.012	0.903	0.013
3	01:35:25.45	30:32:28.8	16.838	0.016	2.118	0.018
4	01:35:03.77	30:30:04.7	17.107	0.008	1.888	0.012
5	01:35:14.13	30:31:50.6	17.298	0.005	2.489	0.007

Note. — The complete version of this table containing all 19350 stars is in the electronic edition of the Journal. The printed edition contains only a sample.

Table 5. Transformation Coefficients from Mould & Kristian Photometry

Band	Zero Point (c_1)	Color Term (c_2)	Number	1σ resid.
Linear fits				
I band	0.127 ± 0.039	-0.065 ± 0.019	197	0.191
V band	0.157 ± 0.034	-0.026 ± 0.021	188	0.232
Weighted mean offsets				
I band	0.005 ± 0.003	$\cdots$	197	0.254
V band	0.121 ± 0.005	$\cdots$	188	0.287